Observation of the Transition $\Upsilon' \to \Upsilon\pi^+\pi^- \to e^+e^-\pi^+\pi^-$

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In a sample of 10 000 Υ' decays observed with our nonmagnetic detector at the Cornell Electron Storage Ring, we find 23 events consistent with the decay $\Upsilon' \to \Upsilon\pi^+\pi^- \to e^+e^-\pi^+\pi^-$. We derive a branching fraction of 0.20 ± 0.07 for $\Upsilon' \to \Upsilon\pi^+\pi^-$ and estimates of the partial width for this decay. The invariant-mass spectrum of the pion pairs shows a strong preference for large di-pion mass.

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The Υ and Υ' are supposed to be $^3S_1$ bound states of a $b\bar{b}$ quark pair, analogous to the ψ and ψ' charmonium states. Soon after the discovery of the upsilons at the Fermilab proton accelerator[1] it was pointed out[2] that the observation in hadronic production of comparable numbers of muon pairs from the Υ' and Υ is inconsistent with the quarkonium model unless the decay $\Upsilon' \to \Upsilon\pi\pi$ is severely suppressed compared to the decay $\psi' \to \psi\pi\pi$.

This decay and other decays in which the heavy quarks do not annihilate account for 75% of the decays of the ψ' but are not available to the ψ. The result is a total width of 215 keV for the ψ', compared to 63 keV for the ψ, and a muon-pair branching fraction of 1%, compared to 7% for the ψ.[3] The Fermilab result for the upsilons requires that the muon-pair branching fractions and hence the total widths of Υ' and Υ be more nearly equal.

We have searched in a sample of about 10 000 Υ' decays for events in which the Υ' decays to $\Upsilon\pi^+\pi^-$ and the Υ then decays to an electron pair, and have found fourteen four prong and nine three prong events which precisely fit this hypothesis. This is the first transition observed between the upsilon states. We derive a branching fraction for $\Upsilon' \to \Upsilon\pi^+\pi^-$ and estimates of the partial width for this decay.

The CUSB (Columbia University—State University of New York at Stony Brook) nonmagnetic detector consists of a drift chamber system inside a segmented shower detector built of sodium iodide and lead glass. Charged-particle trajectories are measured by twelve planes of drift chambers extending between 9 and 21 cm radius from the center of the beam pipe. Six planes have wires parallel to the beam and six others provide a small angle stereo view with $\tan\alpha = \frac{1}{8}$. Tracks are observed over 80% of 4π sr, less 10% because of gaps around 45° in azimuth. The measurement error per wire is typically 0.2 mm and the track reconstruction efficiency is measured to be 99% for azimuthal tracks and 98% in the stereo view for low-multiplicity events.

Our sodium iodide and lead-glass arrays have been described in previous publications.[4,5] The NaI array is segmented into 32 azimuthal sectors, each divided into two polar sectors and five radial layers. The total thickness is about nine radiation lengths. Each quadrant is backed by an 8×8 element array of lead-glass blocks seven radiation lengths thick. The shower detector covers 60% of 4π sr. The energy calibration of the system is established with use of ^{137}Cs and ^{60}Co sources mounted on the NaI crystals, and with use of ^{241}Am sources and light-emitting diodes for the lead-glass blocks. The overall calibration is adjusted with electrons from Bhabha scattering. We find an energy resolution for 5 GeV electrons of $\sigma_E/E = 2.8\%$.

Our analysis includes the following sets of data: (1) 2113 nb^{-1} of integrated luminosity at the $\Upsilon'(9.99)$ peak, (2) 550 nb^{-1} at or near the $\Upsilon(9.44)$ peak, and (3) 2090 nb^{-1} at or near the $\Upsilon'''(10.55)$ peak.

The data were scanned for events resembling Bhabha scatters but containing extra drift chamber tracks. Events with one or two extra tracks (three or four prongs) were considered as candidates. The selection criteria included the following: (1) The observed dielectrom mass must be within 3 GeV of $\sqrt{s}$. (2) The electron shower centroids must be collinear to within 12° in azimuth and the shower centroids from the lead-glass must be collinear to within 15° in polar angle. The maximum possible acollinearity for electrons from $\Upsilon' \to \Upsilon(ee)\pi\pi$ is 7°. (3) To avoid shower energy leakage the electrons must be at least 10° away from the edges of the apparatus in θ and φ. (4) The track vertices must be within ± 5 cm of the interaction-region center. (5) Two of the drift chamber tracks must point to the electron showers. At least one of the remaining tracks must be well separated from the electrons in azimuth (> 10°) and must penetrate at least two layers of the NaI. (6) Three-prong events are rejected if the "pion" deposits more than 40 MeV in the first layer of NaI and more than 30 MeV in subsequent layers. This is unlikely for a pion (it is satisfied by none of the tracks in the four-prong sample) but likely for a photon which has converted in the beam pipe. Figure 1 shows one of our four-prong events.

In our Υ' data sample we observe fourteen four-prong and nine three-prong candidates. Figure 2 shows the observed electron pair mass for all three- and four-prong events. The mean value for the Υ' events is 9458 MeV with average error 193 MeV, compared to $M_\Upsilon = 9435$ MeV.[4,6] The mean missing energy is $\sqrt{s} - M_{ee} = 535$ MeV, compared to $M_{\Upsilon'} - M_\Upsilon = 559$ MeV.[4,6] Kinematic fits are performed with use of the observed angles of all tracks and observed energies of the electrons, giving zero constraint (0C) fits for the three-prong and 2C fits for the four-prong events. Energy deposited by the pions in the NaI is not used for the fitting since it is often not an accurate measure of the pion kinetic energy due to secondary interactions or π-μ decay. All events have good confidence level for the hypothesis $\Upsilon' \to \Upsilon(ee)\pi^+\pi^-$. For 2C fits the average dielectron mass is 9489 MeV with 150 MeV average error.

For four-prong events the most likely backgrounds are the two-photon processes $e^+e^- \to e^+e^-\pi^+\pi^-$, $e^+e^-\mu^+\mu^-$, and for three prongs, radiative Bhabha scatters with the photon converting in the beam pipe. Our Υ and Υ''' data samples contain 2640 nb^{-1} of integrated luminosity and should therefore include a QED contribution 1.25 times that for the Υ' sample. We observe no

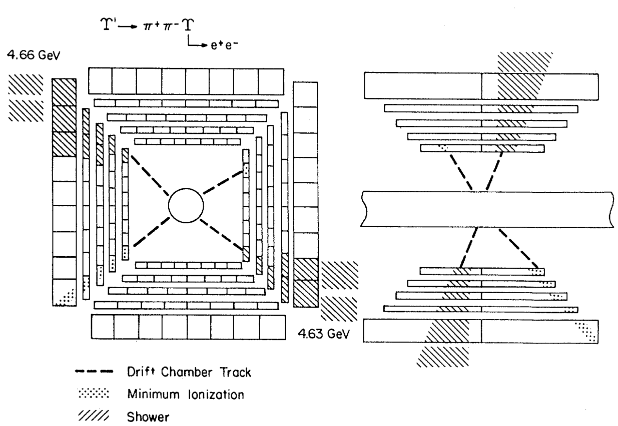

FIG. 1. A display of an event $\Upsilon' \to \Upsilon(ee)\pi^+\pi^-$ in the CUSB detector. All four tracks are seen by the drift chambers and deposit energy in the shower counters. The observed electron pair mass is 9293 MeV.

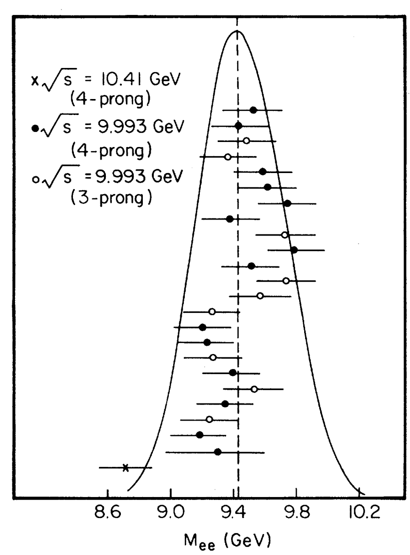

FIG. 2. M_{ee} for events passing our selection criteria. The dashed line is at $M_\Upsilon = 9.435$ GeV. The event from our background data sample ($\sqrt{s} = 10.41$ GeV) is not included in the ideogram.

events in the mass range $160 < \sqrt{s} - M_{ee} < 960$ MeV and one four-prong event in the wider range $(\sqrt{s} - M_{ee}) < 3$ GeV. We take the expected background in the Υ' sample to be less than one event.

Efficiencies for detecting $\Upsilon' \to \Upsilon(ee)\pi^+\pi^-$ were studied with use of a Monte Carlo program. We use for the calculation a di-pion mass spectrum consistent with our observed spectrum, which is peaked toward high mass. The acceptance is 25.4% (17.7% for four-prong events plus 7.7% for three-prong events). We believe that our scanning efficiency for the events is higher than 95% and make no correction.

In the Υ' data sample we observe 13 683 events passing our hadronic event selection criteria and calculate from data taken with beam energies below the Υ' mass a continuum subtraction of $(28 \pm 2.3)\%$, yielding 9851 ± 335 resonance events. The total number of Υ' hadronic decays is calculated to be 14 277 with use of a Monte Carlo–derived factor of 0.69 for the combined trigger and hadronic event selection efficiency.

We calculate, using the 23 observed events and the summed three- and four-prong efficiencies, $B(\Upsilon' \to \Upsilon\pi^+\pi^-)B(\Upsilon \to e^+e^-) = 0.0063 \pm 0.0013 \pm 0.0010$. The estimated systematic uncertainty of 15% comes from the Monte Carlo modeling. $B_{\mu\mu}$ for the Υ has been measured by various collaborations at the Deutsches Elektronen-Synchrotron (DESY) DORIS electron storage ring.[7] We use a weighted average of their results. $B(\Upsilon \to \mu^+\mu^-) = 0.032 \pm 0.008$; assuming $B_{ee} = B_{\mu\mu}$ then gives $B(\Upsilon' \to \Upsilon\pi^+\pi^-) = 0.20 \pm 0.07$. Isospin invariance predicts an additional contribution $B(\Upsilon' \to \Upsilon\pi^0\pi^0) = 0.5B(\Upsilon' \to \Upsilon\pi^+\pi^-)$. We have ignored the contribution to the total width of the Υ' of the decays $\Upsilon' \to e^+e^-, \mu^+\mu^-, \tau^+\tau^-$. If $B_{\mu\mu}(\Upsilon')$ is 2%, our numbers for $B(\Upsilon' \to \Upsilon\pi^+\pi^-)$ and $B(\Upsilon' \to \Upsilon\pi^+\pi^-)B(\Upsilon \to e^+e^-)$ will decrease by 6%.

We now wish to convert the branching fraction to a partial width in order to compare $\Upsilon' \to \Upsilon\pi\pi$ with $\psi' \to \psi\pi\pi$. The total widths of the quarkonium resonances are usually determined as $\Gamma_{tot} \to \Gamma_{ee}/B_{\mu\mu}$; however, $B_{\mu\mu}$ has not yet been measured for the Υ'. We therefore estimate $\Gamma_{tot}(\Upsilon')$ and $\Gamma_{\pi^+\pi^-}(\Upsilon')$ using two less direct methods.

We first write the Υ decay as a sum of decays proceeding through three-gluon intermediate states and of decays proceeding through virtual photons, $\Gamma_{tot}(\Upsilon) = \Gamma_{3g}(\Upsilon) + (3+R)\Gamma_{ee}(\Upsilon)$, with R the off resonance value of $\sigma_{had}/\sigma_{\mu\mu}$. The Υ' decay includes contributions from the $\pi\pi$ and from other possible transitions, $\Gamma_{tot}(\Upsilon') = \Gamma_{3g}(\Upsilon') + (3+R)\Gamma_{ee}(\Upsilon') + \Gamma_{\pi\pi}(\Upsilon') + \Gamma_{other}(\Upsilon')$. Using the expected relation for the three-gluon coupling, $\Gamma_{3g}(\Upsilon')/\Gamma_{3g}(\Upsilon) = \Gamma_{ee}(\Upsilon')/\Gamma_{ee}(\Upsilon)$,[8] we derive $\Gamma_{tot}(\Upsilon') = [\Gamma_{ee}(\Upsilon') + B_{\mu\mu}(\Upsilon)\Gamma_{other}(\Upsilon')]/[B_{\mu\mu}(\Upsilon) - B_{ee\pi\pi}]$, where $B_{ee\pi\pi}$ is the branching fraction for $\Upsilon' \to ee\pi\pi$.

We take values of Γ_{ee} from our recent data. We measure a continuum-subtracted peak resonance yield of $\sigma_{had}(\Upsilon) = 17.9 \pm 0.5 \pm 2.7$ nb, after correction by our Monte Carlo acceptance and efficiency factor of 69%. The systematic uncertainty is dominated by this factor and by the calibration of our luminosity monitor. The peak yield is converted to an area using the resonance shape formula of Jackson and Scharre[9] with values for the Cornell Electron Storage Ring beam energy resolution derived from earlier scans of the Υ,[5,10] and is corrected for the leptonic branching fraction $3B_{\mu\mu}$, giving $\Gamma_{ee}(\Upsilon) = (m_\Upsilon^2/6\pi^2)\int\sigma_{res}dW = 1.07 \pm 0.07 \pm 0.16$ keV. We also measure, as the ratio of Υ' to Υ yields, $\sigma_{had}(\Upsilon')/\sigma_{had}(\Upsilon) = 0.40 \pm 0.03$. This gives, after radiative correction but without correction for the leptonic branching fraction, $\Gamma_{ee}(\Upsilon')/\Gamma_{ee}(\Upsilon) = 0.51 \pm 0.03 \pm 0.04$. These numbers are consistent with values already published.[4,6,7]

Assuming $\Gamma_{other} = 5$ keV,[11] using $B_{\mu\mu}(\Upsilon)$ from DESY DORIS storage rings, and taking (including the neutral pions) $B_{ee\pi\pi} = 0.0095 \pm 0.0020$, we calculate $\Gamma_{tot}(\Upsilon') \simeq 31 + 9 - 7$ keV, and for the charged-pion decays, $\Gamma_{\pi^+\pi^-}(\Upsilon') \simeq 6.2 + 4.4 - 2.7$ keV.

Estimates can also be obtained by using the Fermilab results for hadronic production of Υ and Υ', $(\sigma B_{\mu\mu})_{\Upsilon'}/(\sigma B_{\mu\mu})_\Upsilon = 0.31 \pm 0.03$.[1] The mechanisms suggested as the source of the Υ's, gluon fusion and quark fusion, both predict somewhat larger production of Υ than of Υ'.[12] We take as a reasonable limit $\sigma(\Upsilon') < \sigma(\Upsilon)$. Correcting the Fermilab measurement for the $(30 \pm 10)\%$ feed-down from Υ' to Υ through $\pi\pi$ decays then gives $B_{\mu\mu}(\Upsilon') > (0.40 \pm 0.05)B_{\mu\mu}(\Upsilon)$. The use of our ratio $\Gamma_{ee}(\Upsilon')/\Gamma_{ee}(\Upsilon)$ and the DESY DORIS $B_{\mu\mu}(\Upsilon)$ yields $\Gamma_{tot}(\Upsilon') < (1.3 \pm 0.2)\Gamma_{tot}(\Upsilon) = (1.3 \pm 0.2)(33 + 11 - 7)$ keV, and $\Gamma_{\pi^+\pi^-}(\Upsilon') < 8.4 + 6.4 - 4.1$ keV.

The 1-standard-deviation (1σ) statistical errors of these results are slightly misleading because the uncertainty is dominated by the large error of $B_{\mu\mu}$ appearing in denominators. We therefore note that both calculations give 2σ limits of $\Gamma_{tot} < 90$ keV and $\Gamma_{\pi^+\pi^-} < 30$ keV.

The corresponding widths measured for the charmonium system are $\Gamma_{tot}(\psi) = 63 \pm 9$ keV, $\Gamma_{tot}(\psi') = 215 \pm 40$ keV, and $\Gamma_{\pi^+\pi^-}(\psi') = 70 \pm 14$ keV.[3] Gottfried[13] and more recently Yan[14] have

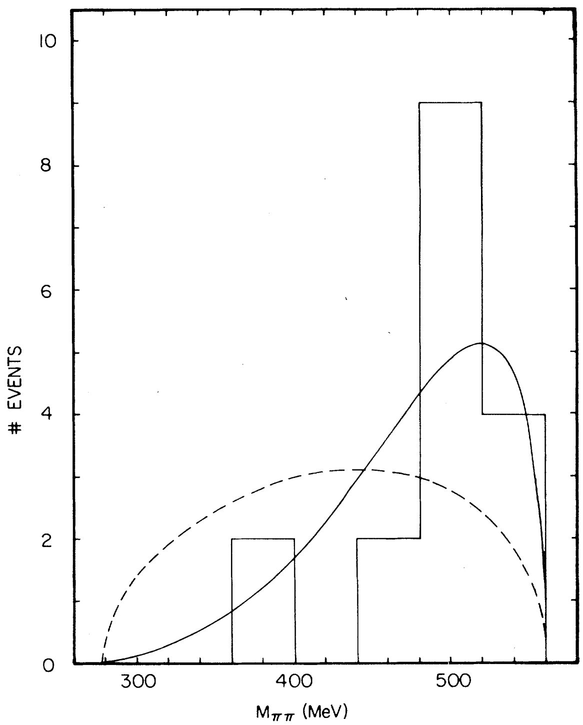

FIG. 3. $M_{\pi\pi}$ for our four-prong events. The solid curve is from Ref. 7 and the dashed curve is from a phase-space model. The histogram and curves are normalized to equal areas.

predicted, using a gluonic radiation multipole expansion technique within quantum chromodynamics, that the small radius r of the Υ' and Υ compared to the ψ' and ψ should result, for the case of spin-1 gluons, in a suppression of the partial width of the decay by a factor of $\langle r_{\psi'}{}^2\rangle^2/\langle r_{\Upsilon'}{}^2\rangle^2 \simeq 10$. Our results are consistent with the factor of 10 and imply a suppression of at least a factor of 2.

Cahn and Brown[15] have predicted the shape of the di-pion mass spectrum and Yan includes a similar calculation in his study of pionic transitions.[14] Figure 3 shows Yan's prediction, a phase-space prediction which assumes s-wave emission of the pions, and a histogram of $M_{\pi\pi}$ for four-prong events from our Υ' data. The events have been refitted constraining the dielectron mass to the Υ mass, resulting in errors for the di-pion mass which are negligible compared to the bin width. Three events with electrons slightly outside the fiducial boundaries have been added to the 14 within. Our observed distribution disagrees with the phase-space distribution by 3.5σ and is clearly consistent with that of Yan. A similar peaking at high $M_{\pi\pi}$ has been observed at the Stanford Linear Accelerator Center SPEAR storage ring for the $\psi' \to \psi\pi\pi$ decays.[16]

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